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OTTAWA CARLING TS - GROUNDING SYSTEM STUDIES

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Current injection tests were conducted at Ottawa Carling TS to measure the ground potential rise and touch and step potentials. Soil resistivity at the station was also measured. The ground potential rise and touch and step potentials were found to be within safe limits for an ultimate HV station fault current of 10 kA. Models were developed to generalize the results.

1.0 INTRODUCTION

Ottawa Carling TS is located at the corner of Carling Avenue and Merivale Road in the city of Ottawa. The HV facilities at the station include three transformer banks each consisting of three 5 MVA, 63.5-110/11 kV single phase transformers connected in Y/Δ, three transformers rated 20 MVA, 110/12 kV Y/Δ, two 115-kV overhead lines to Ottawa Merivale TS and two 115-kV pipe-type cables to Ottawa Lisgar TS. The station is normally supplied from Merivale TS. The station supplies Ottawa Hydro loads through twenty-four 14-kV and fifteen 4-kV feeders. The grounding system at the station is complex due to an irregular ground grid and the extensive network of multigrounded distribution neutrals. Also the area may have other underground services connected to the station grounding system. This could make design-type calculation of the grounding system performance at the station difficult. Therefore, simulated fault current tests were done at the station to determine the station grounding system performance. The objectives of the tests were to confirm the adequacy of the grounding system performance at the station with respect to public safety, station security and protection of communication cables and to validate models to generalize the results. Measurements were limited to the station ground potential rise and touch and step potentials. The project was requested and funded by Design and Development Division - Transmission. The tests were conducted at Ottawa Carling TS on June 20, 1986.

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2.0 TEST PROCEDURE

Figure 1 shows the layout of Ottawa Carling TS with respect to the grounding tests. A test current of about 2 A at 120 V, 67 Hz from a gasoline-powered generator was injected into remotely grounded spare pairs (five pairs paralleled) of the communication cable east towards Bronson Sub as shown in Figure 2. The following measurements were made at Ottawa Carling TS:

(1) Station ground potential rise between a remotely grounded communication cable towards the south and local station ground,

(2) Fence potentials and station touch and step potentials,

(3) Soil resistivity.

Potentials (both magnitude and phase angle) were measured with respect to 1.0/0 A injected current using an HP3582A network analyzer in conjunction with a differential amplifier. A Ritz clip-on 5 VA, 150:5 A CT with 0.66 Ω shunt was used to measure the current signal. Telephone- style carbon protectors were used to limit the potential to local ground on the input wiring to the instrumentation in the event of a system fault. Heavy connections were made from the frame of the instrumentation to the station ground for personnel safety. A north-south resistivity survey using the Wenner method was done east of the station property. A Megger DET-2 ground resistance tester was used to take these readings. Assistance was obtained from Regional and District Operations, Station and Lines Maintenance, District P&C, Head Office and Ottawa Hydro staff in conducting the tests.

3.0 TEST RESULTS

3.1 Measured Soil Resistivity

The apparent soil resistivities calculated from the measured Wenner readings (equation 7.1 of the Grounding Guide /1/) are given in Table 1 along with fitted two-layer model parameters.

TABLE 1

CARLING TS - SOIL RESISTIVITIES

Probe Spacing (m)	Apparent Resistivity (Ω.m) Measured	Modelled
2	46.4	54.0
5	89.5	90.0
10	148.3	138.0
20	296.6	180.0
50	205.8	210.0

Fitted Two-Layer Model Parameters

ρ_1 = 44 (Ω.m)
ρ_2 = 220 (Ω.m)
d = 2.2 m

3.2 Measured Ground Potential Rise

The ground potential rise measured on the remotely grounded aerial communication cable towards the south along Merivale Road was 35.3/-45 mV/A. Estimated correction factors were applied to compensate for the shielding of the communication cable and induction due to currents in the distribution neutrals going south along Merivale Road and in the skywires of the 115-kV lines going south to Merivale TS. The resulting station ground potential rise is about 55.9/4 mV/A which is about 558 V for an ultimate HV station fault current of 10 kA.

3.3 Measured Touch and Step Potentials

Potential measurements were repeated at several locations and the highest measured values are given in Table 2 along with modelled results. For the above fault current of 10 kA, the maximum measured station touch (mesh) potential and fence touch potential to the public outside are 53 V and 69 V respectively.

TABLE 2

CARLING TS - MEASURED AND MODELLED POTENTIALS

Potential	Measured (mV/A)	Modelled (mV/A)	
		(1)	(2)
Ground Potential Rise	55.9/4	55.1/42	41.6/51
Fence Outside Touch	6.88/47	5.53/42	4.18/51
Station Touch (Mesh)	5.33/50	5.09/42	3.84/51
Station Step	1.87/52	2.21/42	1.67/51
Fence To Station Ground	14.5/48	-	-
Between Station Gates	0.07/116	-	-
Cable Pan Touch	0.90/54	-	-

(1) Fault current supplied from communication cable (test condition).
(2) Fault current supplied from 115-kV overhead line to Merivale TS.

4.0 MODELLED RESULTS

Appendix A summarizes various formulas used in the calculations other than those given in the Grounding Guide /1/ and IEEE Guide /2/.

4.1 Soil Resistivity

The measured soil resistivity data was interpreted as a two-layer model (Table 1) using the method given Appendix D of the Grounding Guide /1/. An equivalent soil resistivity of 120 Ω.m was obtained from the two-layer model based on an estimated equivalent station radius of 64 m.

4.2 Isolated Station Ground Resistance

The station ground resistance was calculated as 0.54 Ω based on an estimated station radius of 64 m and 1670 m of buried ground conductors (Equation 3.3 of the Grounding Guide /1/).

4.3 Conductive Equivalent Circuit

Figure 3 shows the conductive equivalent circuit for the test condition. The impedances were calculated using simplified formulas for Carson's earth return self impedances which carry the conductive component of the fault current.

For the 159 mm^2 (19 #8 AWG) aluminum-weld skywire of the double-circuit line to Merivale TS, the calculated conductive earth return self impedance is about $1.12\underline{/58}$ Ω/km. From the ladder network of the skywire self impedance and a tower footing resistance of 15 Ω, calculated assuming a footing radius of 2 m and a footing spacing of 10 m, a lumped conductive impedance Z_{c1} of $1.38\underline{/29}$ Ω was calculated assuming a tower span length of 114 m.

For the two HV pipe-type cables which are run in parallel along Carling Ave to Lisgar TS, a conductive circuit impedance Z_{c2} of about $3.45\underline{/76}$ Ω was calculated including the mutual effect assuming a separation distance of about 1 m. The calculation details are given in/3/. With extensive distribution neutrals, the station ground impedance at Lisgar TS should be very small and was neglected compared to the pipe impedance.

For the parallel combination of the twenty-four 14-kV and fifteen 4-kV distribution feeder neutrals, a net impedance Z_{c3} of $0.068\underline{/72}$ Ω was calculated assuming that the feeders are grouped in four directions. In each direction, the feeders were assumed to be run in ducts for about 200 m near the station and then carried on overhead poles as estimated from drawings. A GMR of 0.2 m was assumed in the ducts.

Ottawa Carling TS is normally supplied through the HV overhead lines from Merivale TS. A shielding factor, S, of $0.68\underline{/-13}$ was calculated for the skywire which is the conductive component of the fault current applied to the conductive equivalent circuit. The inductive component of the skywire current calculated as $(1-S)I_f$ is $0.37\underline{/24}$. For the test condition with the simulated fault current injected via the communication cable, a shielding factor of about $0.90\underline{/-22}$ was estimated for the communication cable.

Impedance of the water pipes leaving the station was neglected in the model assuming well insulated pipe joints. The communication cable sheath impedance was also neglected since previous measurements at other stations have indicated relatively small fault current splits in communication cable sheaths.

From Figure 3, the resulting interconnected station ground impedance is $0.06\underline{/64}$ Ω.

4.4 Modelled Current Splits

The conductive equivalent circuit in Figure 3 was solved for an injected station fault current of $1.00\underline{/0}$ A as follows:

(1) With the fault current injected to the test circuit (communication cable), the shielding factor of the communication cable was applied to the conductive equivalent circuit. The inductive component of the fault current returns through the communication cable sheath.

(2) With the fault current injected to one circuit of the double-circuit HV overhead line, the shielding factor of the skywire was used to solve the conductive equivalent circuit. The total skywire current is the sum of the conductive and inductive components.

The calculated current splits in each of the above cases are given in Table 3.

TABLE 3
CARLING TS - MODELLED CURRENT SPLITS

Current Path	Current Split (A)	
	(1)	(2)
Injected Current	1.00/0	1.00/0
Skywire	0.040/13	0.401/24
HV Cable Pipe	0.016/-34	0.012/-25
Distribution neutrals	0.815/-30	0.616/-21
Station Ground	0.102/42	0.077/51
Test Circuit (Comm. Cable)	0.38/64	-

(1) Current injected to the test circuit (Communication Cable)
(2) Current injected to the HV overhead line

4.5 Modelled Ground Potential Rise

The ground potential rise V_g at Ottawa Carling TS was calculated as $I_g R_g$ where I_g is the modelled station ground current split and R_g is the station ground resistance. Table 2 compares the modelled values with the measured results. For an ultimate fault current of 10 kA, the modelled GPR is about 416 V.

4.6 Modelled Touch and Step Potentials

The station touch (mesh) and step potentials were calculated using equations 3.6 of the Grounding Guide /1/ and 73 of IEEE Guide 80 /2/ respectively and the fence touch potential to the public outside was calculated using equation 3.10 of the Grounding Guide /1/ assuming that the fence is connected to the station ground grid. The modelled values are given in Table 2 along with the measured results. For an ultimate HV fault current of 10 kA, the modelled station touch (mesh) and step potentials and the fence touch voltage are 38 V, 17 V and 42 V respectively.

5.0 DISCUSSION OF RESULTS

(1) The station ground impedance was reduced to 0.06/64 Ω mainly due to the extensive multigrounded distribution system. The estimated isolated station ground resistance is about 0.54 Ω.

(2) As a result of the above, the station ground potential rise (GPR) is substantially reduced and is well under the recommended limit of 3 kV for an ultimate HV fault current of 10 kA. The corrected measured GPR compares reasonably with the modelled value.

(3) For the station supplied from Merivale TS via the HV overhead lines, only about 68% of the fault current enters the station grounding system due to the shielding of the skywire. In the future if the station is fed from Lisgar TS via the HV pipe-type cables, about 90 % of the fault current would then return through the cable pipes due to the shielding efficiency, resulting in even lower station GPR.

(4) The modelled station touch and step potentials agree reasonably with the measured values. The tolerable limits of touch and step potentials calculated using equations 2.4 and 2.2 of the Grounding Guide /1/ are 174 V and 204 V respectively for an average person standing on bare soil. The station touch and step potentials of approximately 50 V and 20 V for an ultimate HV fault current of 10 kA are both under the tolerable limits.

(5) The measured and modelled fence touch potentials of about 70 V and 40 V respectively for an ultimate HV fault current of 10 kA are both under the tolerable limit of 174 V. Measurements could not confirm whether the station fence is connected to the station ground grid as the measured voltages vary over a wide range.

6.0 CONCLUSIONS

(1) The equivalent soil resistivity at Ottawa Carling TS is about 120 Ω.m based on a two-layer soil model obtained from Wenner test data for an estimated station radius of 64 m.

(2) The isolated station ground resistance was calculated as 0.54 Ω based on an estimated station radius of 64 m and 1670 m of buried ground conductors. The calculated interconnected station ground impedance is about 0.06/64 Ω, mainly due to the extensive multigrounded distribution neutrals. Only about 8 % of the station fault current was found to enter the station ground. As a result, the station ground potential rise is considerably reduced.

(3) The ground potential rise (GPR) at Ottawa Carling TS is well under the recommended limit of 3 kV for an ultimate HV fault current of 10 kA. The measured station GPR is about 55.85/4 mV/A (about 560 V for a fault current of 10 kA) with the test current injected to a remotely grounded communication cable. Reasonable agreement was obtained between the measured and modelled values. For the station supplied from Merivale TS, the GPR would be about 420 V as calculated for the above fault current of 10 kA, due to the shielding efficiency (about 68 %) of the skywire. The GPR would be further reduced should the station be supplied from Lisgar TS in the future via the HV pipe-type cables, due to the high shielding efficiency of pipe-cables (about 90 % of the fault current would return through the cable pipe with only about 10 % entering the station grounding system).

(4) The station touch (mesh) and step voltages and fence touch voltage on the outside (public) for the above fault current of 10 kA were found to be well under the tolerable limits calculated for the station.

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1. Ontario Hydro, Guide for Grounding, 1983 Revision.

2. IEEE Standard 80, IEEE Guide for Safety in AC Substation Grounding, 1986 Revision.

3. E.P. Dick, "Strachan TS Grounding System Calculations", Ontario Hydro Research Report No 83-433-K, November 7, 1983.

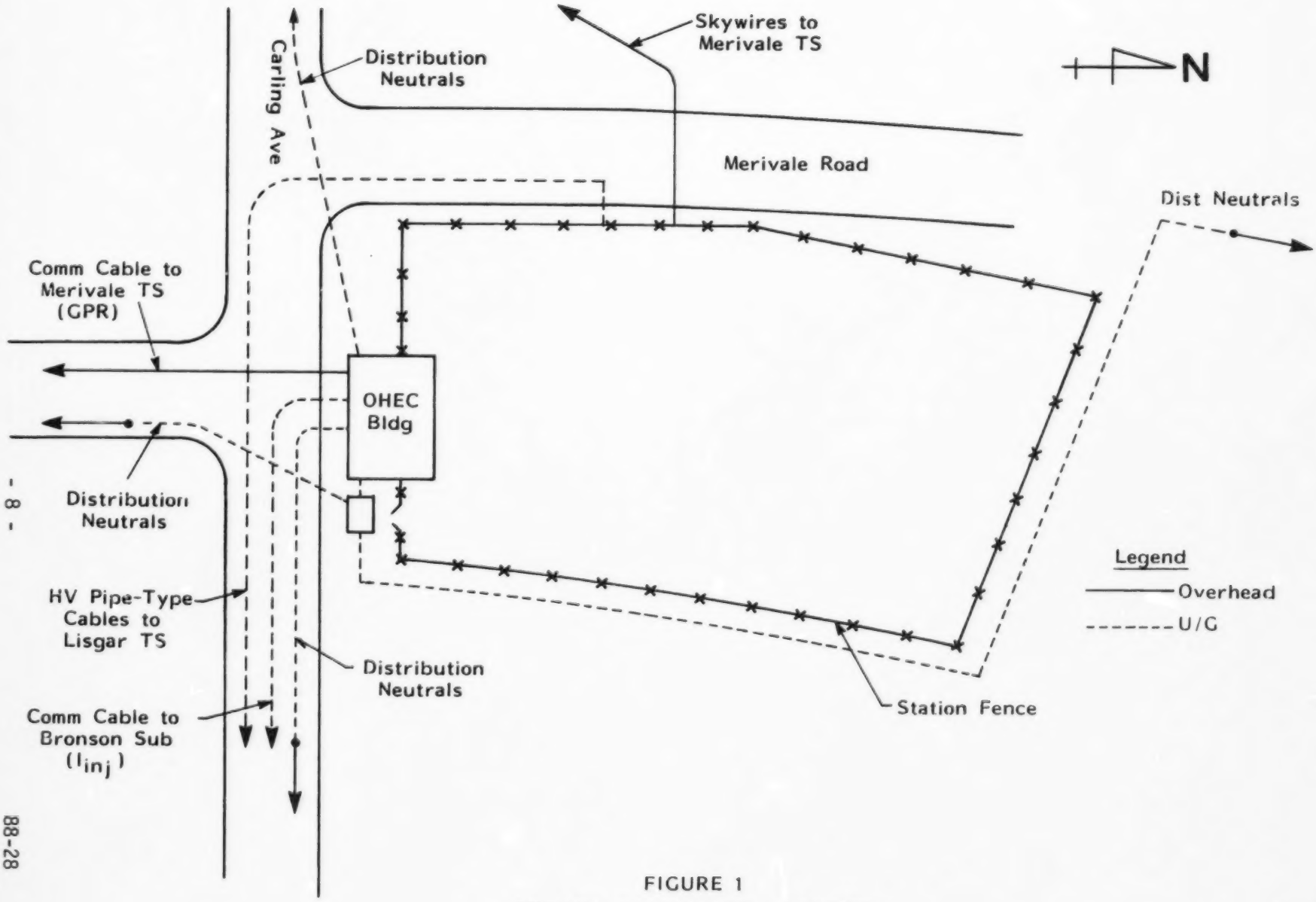

FIGURE 1
OTTAWA CARLING TS - LAYOUT

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176345-RD

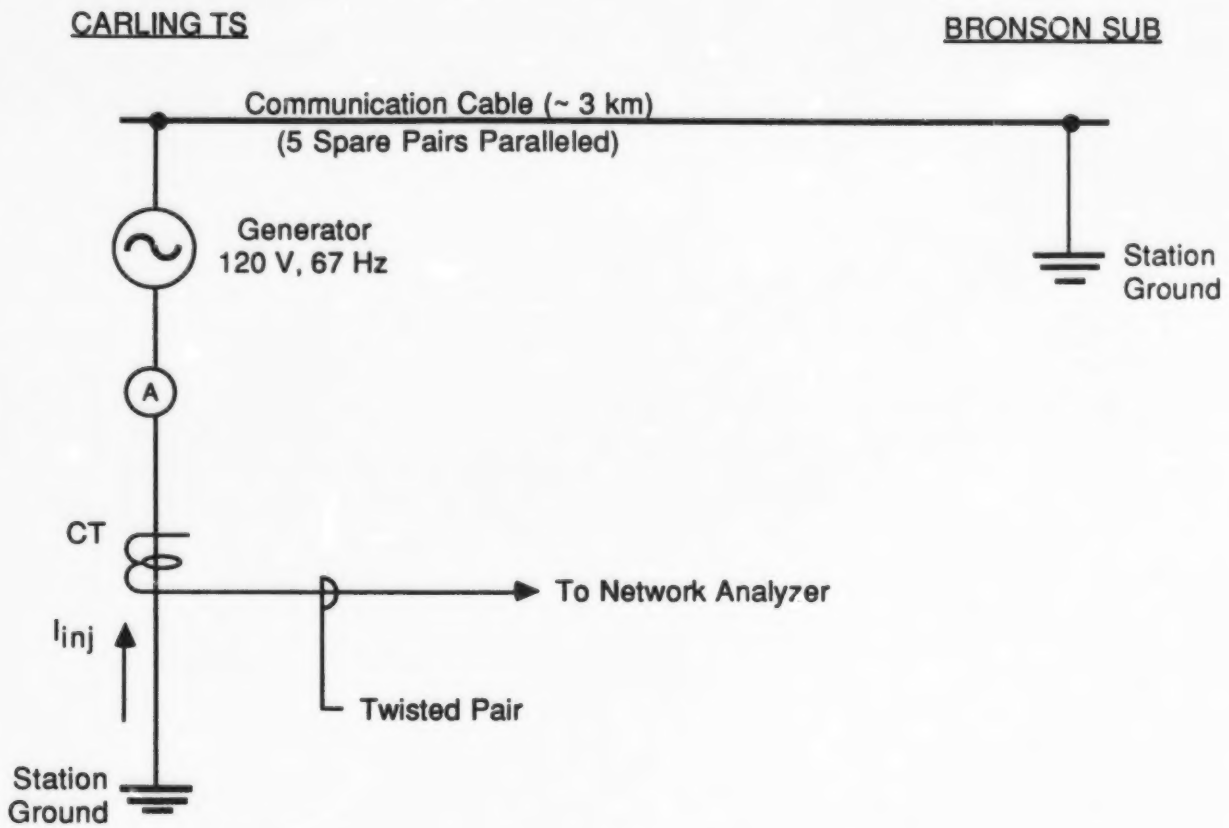

FIGURE 2

OTTAWA CARLING TS
FAULT SIMULATION CIRCUIT

176344-RD
JA 3 DISK
88-28

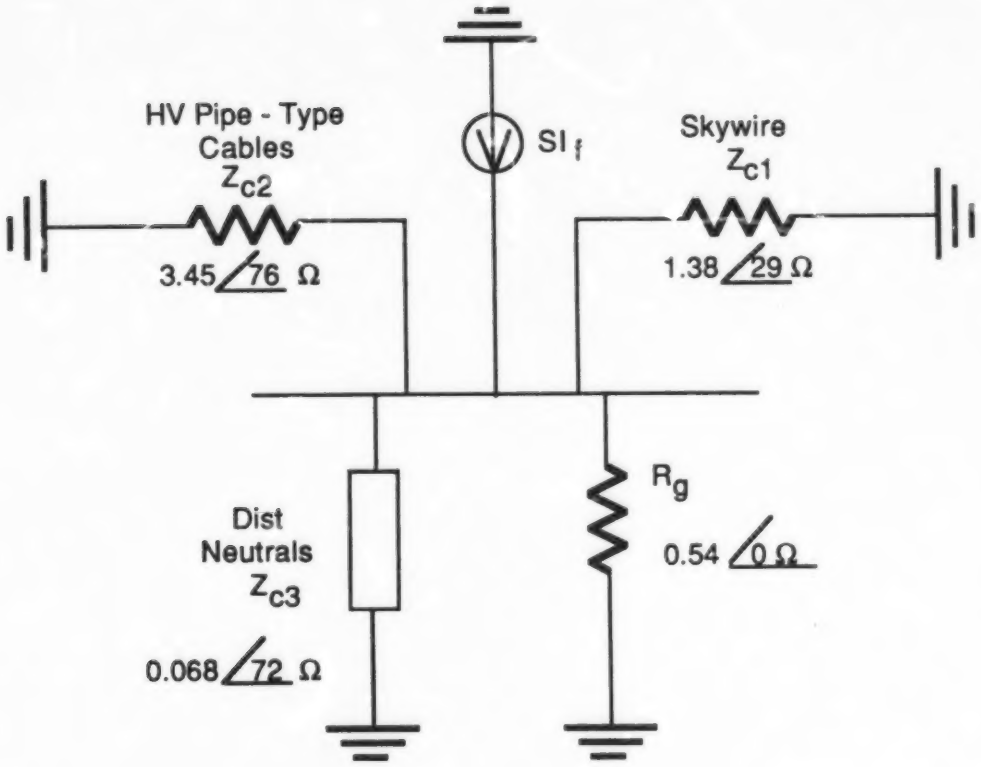

FIGURE 3

OTTAWA CARLING TS
CONDUCTIVE EQUIVALENT CIRCUIT

APPENDIX A
SUMMARY OF FORMULAS USED IN GROUNDING CALCULATIONS

1. Conductor Earth Return Self Impedance, Z_s

$$Z_s = R_s + jX_s \quad (\Omega/km) \tag{1}$$

$$R_s = 0.059 + R_{ac} \quad (\Omega/km) \tag{2}$$

$$X_s = 0.0377 \ln \left(\frac{8440\ \rho_s}{GMR^2}\right) \quad (\Omega/km) \tag{3}$$

Where, R_{ac} = conductor ac resistance (Ω/km)
ρ_s = soil resistivity (Ω.m)
GMR = conductor geometric mean radius (m)

For pipes or shields, R_{ac} and X_{ac} (conductor internal reactance added to X_s) are calculated as shown in reference/3/.

2. Conductor Earth Return Mutual Impedance, Z_m

$$Z_m = R_m + jX_m \quad (\Omega/km) \tag{4}$$

$$R_m = 0.0377 \tan^{-1} \left(\frac{8440\ \rho_s}{GMD^2}\right) \quad (\Omega/km) \tag{5}$$

$$X_m = 0.0377 \ln \left(\frac{8440\ \rho_s}{GMD^2} + 1\right) \quad (\Omega/km) \tag{6}$$

Where, ρ_s = soil resistivity (Ω.m)
GMD = geometric mean distance between conductors (m)

3. Tower Footing Resistance, R_t

$$R_t = \frac{\rho_s}{2\pi}\left[\frac{1}{r} + \frac{2.707}{w}\right] \ (\Omega) \qquad (7)$$

Where, ρ_s = soil resistivity (Ω.m)
r = equivalent footing radius (m)
w = footing spacing (m)

4. Chain Impedance of Skywires, Z_c

$$Z_c = \sqrt{Z_s \ell R_t} \ (\Omega) \qquad (8)$$

Where, Z_s = conductor earth return self impedance (Ω/km)
ℓ = span length (km)
R_t = tower footing resistance (Ω)

5. Station Earth Potential to Remote Ground $V_{(x)}$

For disk-like electrode in uniform earth,

$$V_{(x)} = \frac{\rho_s I_g}{2\pi r} \sin^{-1}\left(\frac{r}{x}\right) \qquad (9)$$

Where, ρ_s = soil resistivity (Ω.m)
I_g = ground current (A)
r = station radius (m)
x = distance from station centre (m)